

Comparison of Super-Cooled Liquid Water Cloud Properties Derived from Satellite and Aircraft Measurements

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*FAA In-flight Icing/Ground De-icing International Conference
Chicago, Illinois
June 16-20, 2003*

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ABSTRACT

A theoretically based algorithm to derive super-cooled liquid water (SLW) cloud macrophysical and microphysical properties is applied to operational satellite data and compared to pilot reports (PIREPS – from commercial and private aircraft) of icing and to in-situ measurements collected from a NASA icing research aircraft. The method has been shown to correctly identify the existence of SLW provided there are no higher-level ice crystal clouds (i.e. cirrus) above the SLW deck. The satellite-derived SLW cloud properties, particularly the cloud temperature, optical thickness or water path and water droplet size, show good qualitative correspondence with aircraft observations and icing intensity reports. Preliminary efforts to quantify the relationship between the satellite retrievals, PIREPS and aircraft measurements are reported here. The goal is to determine the extent to which the satellite-derived cloud parameters can be used to improve icing diagnoses and forecasts.

INTRODUCTION

Aircraft icing is a significant concern to the general aviation community and efforts are underway to improve real-time icing diagnoses and forecasts. Satellite data can be used to deduce icing conditions in many cases [1]. Geostationary satellites provide both high spatial and temporal resolution and should play an important role in real-time icing diagnosis algorithms. A suite of algorithms has been developed to deduce the cloud amount, temperature, height, optical depth, hydrometeor phase, particle size, and water path from satellite data [2], [3]. The phase and temperature data are used to

diagnose the presence of super-cooled liquid water (SLW), a prerequisite for aircraft icing. The method has been shown to correctly identify the existence of SLW for over 98% of the aircraft reports of positive icing provided there are no higher level ice crystal clouds (i.e. cirrus) above the SLW deck [4]. Excellent correspondence has also been found between the satellite SLW identification and SLW cloud top penetrations made by the NASA Glenn Research Center's Twin Otter icing research aircraft (hereafter, the NGTO) [5]. Once the SLW determination is made, the particle size and optical depth or liquid water path retrievals should be valuable for estimating the potential for aircraft icing conditions. During the past several years, the NGTO has conducted numerous flight experiments to sample cloud microphysical properties and icing conditions in clouds composed of SLW including clouds composed of Super-cooled Large Droplets (SLD). The satellite-derived cloud parameters are being deduced from Geostationary Operational Environmental Satellite (GOES-8) 4-km imagery that coincide with all of the NGTO flight days dating back to 1997 in an effort to validate the satellite products and determine their potential use for improved icing diagnoses and forecasts. Here, we present comparisons of satellite and aircraft cloud microphysical parameters obtained during the 1997/ 1998 winter flight series in the vicinity of the Ohio/Great Lakes region. Preliminary correlations between PIREPS icing intensity reports and the satellite retrievals are presented and associated problems are discussed. This past winter (Jan-Apr, 2003), the satellite analyses were conducted in near real-time and made available on the World Wide Web to support the 2003 NGTO icing campaign. A brief qualitative comparison between satellite and observer notes during this campaign is also presented.

RESULTS

An example of cloud properties derived from GOES-8 in real-time at 1745 UTC on February 13, 2003 to support the NGTO 2003 flight series is shown in figure 1. Much of the region is covered by low to mid level clouds. The panel in the upper left depicts results of the cloud mask and hydrometeor phase identification. Green denotes cloud free areas, red denotes clouds identified to be composed of ice crystals and the blue shades denote water clouds. Cyan indicates the location of SLW (water clouds with radiating temperatures below freezing) while the dark blue denotes warm water clouds. Much of the area is covered by SLW clouds. Also shown in Figure 1 are the cloud temperature, liquid water path and water droplet effective radius. The liquid water path (or vertically integrated liquid water content) is estimated from the satellite derived cloud optical depth and effective radius using geometric optics. The horizontal variability in the cloud microphysical properties derived from GOES-8 is significant, particularly across central Ohio where the range in liquid water path is nearly an order of magnitude (from 50 to over 400 g/m²) and the water droplet radii increase in value from about 8 μm in the west to greater than 20 μm in the central part of the state. On this day, forecasters from NCAR's Research Application Program (RAP) who maintain constant communication with the in-flight crew of the NGTO via satellite phone, used the real-time satellite products to direct the NGTO into the region the satellite depicted as being composed of large water droplets and liquid water paths. The NGTO encountered moderate icing and confirmed the presence of large droplets and relatively high ice water contents (Ben Bernstein, personal communication). Pilot reports of icing intensity between 1600 and 2200 UTC are shown in figure 2. A value of 3 indicates 'light' icing. A northwest to southeast swath of light icing was reported from north-central Ohio thru southwest Pennsylvania and northeast West Virginia. The satellite retrievals over much of this swath indicate the presence of ice crystals. It's quite likely that these cold clouds with temperatures less than -20 C are mixed phase (composed of ice and water hydrometeors) and may explain why none of the PIREPS indicate severities greater than 'light' since ice crystal nucleation and growth processes could have depleted some of the available SLW. However, we have no validation of this since the NGTO sampled the portion of cloud over north-central Ohio where the satellite retrievals indicated the presence of water droplets.

The satellite cloud parameters described above have undergone extensive validation/comparison with surface based remote sensing techniques and aircraft measurements [6]. A recent comparison of liquid water paths derived from GOES-8 and that derived from surface-based microwave radiometers [7] is shown in figure 3. VISST (Visible Infrared Solar-infrared Split-window Technique) denotes our daytime satellite algorithm [2], [3]. The microwave radiometer retrievals

are performed routinely as part of the ARM (Atmospheric Radiation Measurement) program, a long-term observation program being conducted by the Department of Energy over the U.S. southern Great Plains. 55% of the data shown here are comprised of clouds with some SLW. The agreement between the satellite and surface-derived liquid water paths is very good (4.3 +/- 96.3 g/m²) especially considering the difficulties associated with matching high frequency point measurements from the surface radiometer to larger domain averaged satellite data taken every 15 minutes. In figure 4, a comparison between satellite-derived water droplet radius and droplet sizes measured from NGTO SLW cloud top penetrations during the 1997/1998 winter flight series [8] is shown. The satellite retrievals represent the mean in a 0.3 degree lat/lon box centered over the location of the aircraft measurements. The error bars represent the standard deviation in the satellite pixel-level retrievals. The aircraft data have been stratified into four classes [8]. A reasonable degree of correlation is found as the satellite-derived droplet sizes increase with increasing aircraft-deduced droplet size. Note that the droplet sizes are defined differently for the two datasets. The concept of defining an effective dimension to characterize the size distribution found in real clouds is appropriate but also the subject of some controversy and depends on the application from which it is derived or for how it is to be applied. Further elaboration on this problem is beyond the scope of this document but we note that the aircraft median volume radius is larger than the satellite effective radius as expected when considering each definition.

An initial attempt has been made to correlate icing severity or intensity reports from PIREPS with the satellite-derived cloud parameters described above. The results depicted in figure 5 were constructed by matching 0.3 degree areal mean cloud properties derived from GOES with over 800 positive icing PIREPS. The analyses were conducted using the March 2000 dataset over the central U. S. described in [3] and the dataset coinciding with the NGTO 1997/1998 flight days described in [5]. The fact that the relationship between the mean cloud parameters and icing intensities behaves as expected (droplet size and water path increase while cloud temperature decreases with increasing icing intensity) is very encouraging. However, the large degree of scatter (represented by the large standard deviations) in the satellite parameters requires further examination. Possible explanations for the scatter in figures 4 and 5 include spatial mismatches between the satellite and aircraft datasets particularly in regions where there are strong gradients in the cloud properties, sampling issues with the aircraft microphysics probes and possible errors in the satellite retrievals at certain scattering angles where the phase function is strongly peaked (i.e. rainbow and glory features at scattering angles > 140°). The latter problem is under investigation and correction efforts underway [3]. Another possible explanation for the scatter in figure 5 is related to the aircraft dependence of icing severity, which will be discussed further in the next section.

DISCUSSION AND CONCLUDING REMARKS

The satellite-derived cloud microphysical properties described here show great promise for icing diagnosis and possibly forecasting applications. The potential for obtaining high frequency (15 minute) observations of SLW cloud properties at high spatial (4km) resolution needs to be exploited. We seek to develop useful icing indicators based on the satellite retrievals perhaps with additional guidance from assimilation and forecast models. The satellite retrievals have been validated over a wide range of conditions. Qualitatively, the satellite retrievals show good correspondence with aircraft icing reports. Note that in figure 1, there are no icing reports in SLW regions composed of low water paths, small droplet sizes and/or warmer cloud temperatures. In other cases (not shown) more frequent icing reports and higher intensities are reported in regions with colder clouds composed of larger droplet radii and larger liquid water paths. This general correspondence has been noted in many of the satellite cloud property images and corresponding PIREPS that we've examined and agrees with our current understanding of the relationship between SLW cloud microphysics and icing intensity or severity. It is also interesting to note that the satellite products proved useful in directing NGTO flights during the 2003 winter flight series. Preliminary observations noted by the NGTO flight scientist showed promising correspondence between icing conditions and the satellite cloud properties (Ben Bernstein, private communication).

Of particular interest in advancing satellite techniques for icing diagnosis is the development of meaningful real-time severity indices that can be used by pilots and air traffic controllers. This requires quantifying the relationship between satellite-derived cloud properties and icing severity. A preliminary effort has been reported here. However, this is not a straightforward problem primarily because icing severity is a poorly defined condition and depends on how the aircraft performance is affected [9]. For a given ice accretion, different aircraft will respond in different ways. Some of the scatter seen in figure 5 could be due to this fact. It is not uncommon to find large differences in PIREP intensity reports with a high degree of co-location. Besides airframe dependence, another possible explanation includes latency in reporting (particularly for faster aircraft) that could translate to large collocation errors between the satellite parameters and the icing observations (rather than the icing reports).

In future analyses we will stratify the PIREPS by aircraft type to try and reduce the scatter and develop more statistically significant correlations than those shown in figure 5. Some improvements in the satellite retrievals are also expected. Much more work is needed to improve the utility of the satellite products including more analyses of the NGTO data and more flights preferably designed with satellite validation in mind and using real-time satellite products as a guide.

ACKNOWLEDGMENTS

This research is funded by the NASA Earth Science Enterprise and the NASA Aviation Safety Program through the NASA Advanced Satellite Aviation-weather Products Initiative. Additional support was provided by the Environmental Sciences Division of U.S. Department of Energy Interagency Agreement DE-AI02-97ER62341 through the ARM Program.

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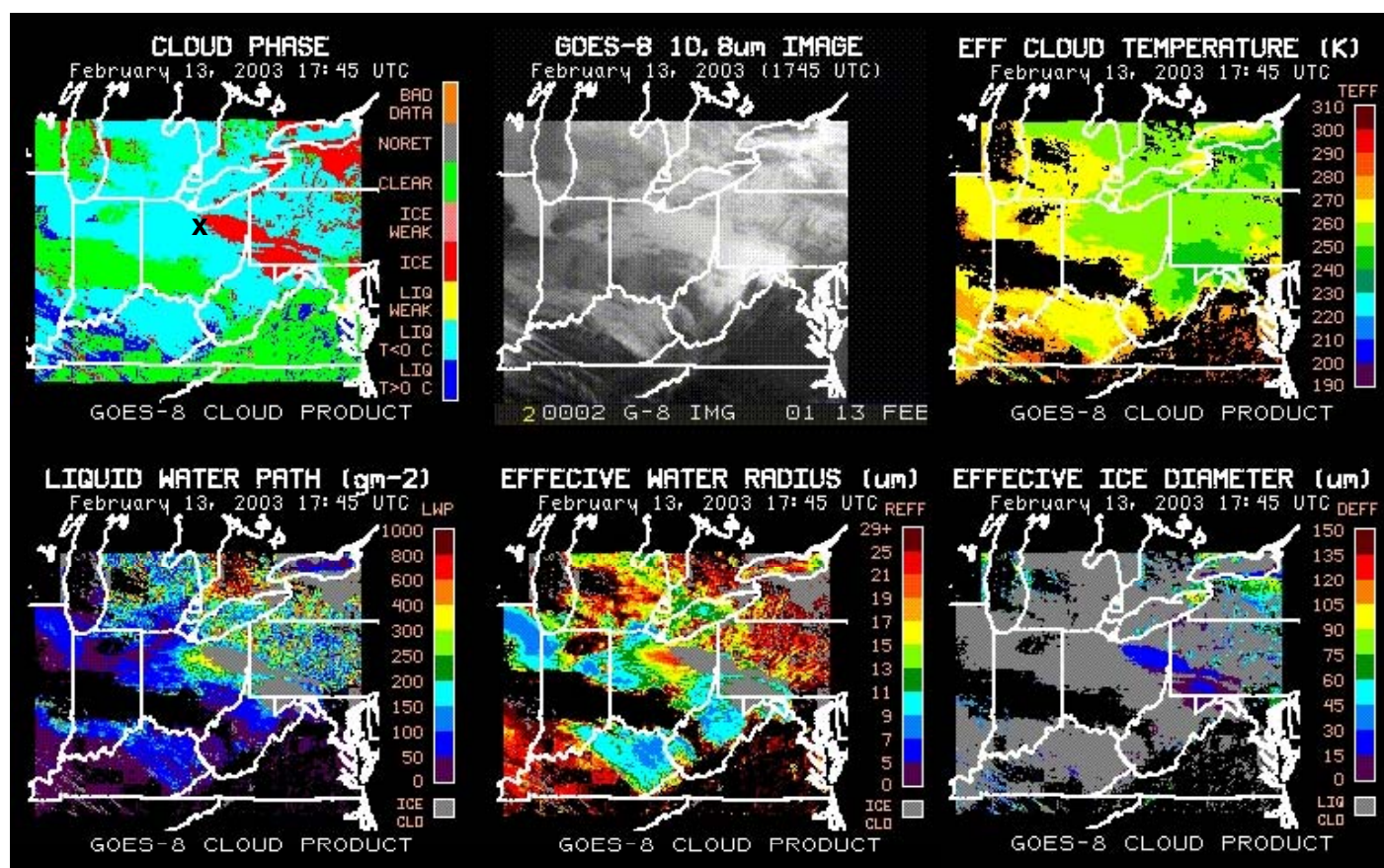


Fig. 1. GOES-8 infrared imagery and derived cloud properties at 1745 UTC on Feb. 13, 2003. The black 'X' in the cloud phase panel indicates approximate location of NGTO aircraft location.

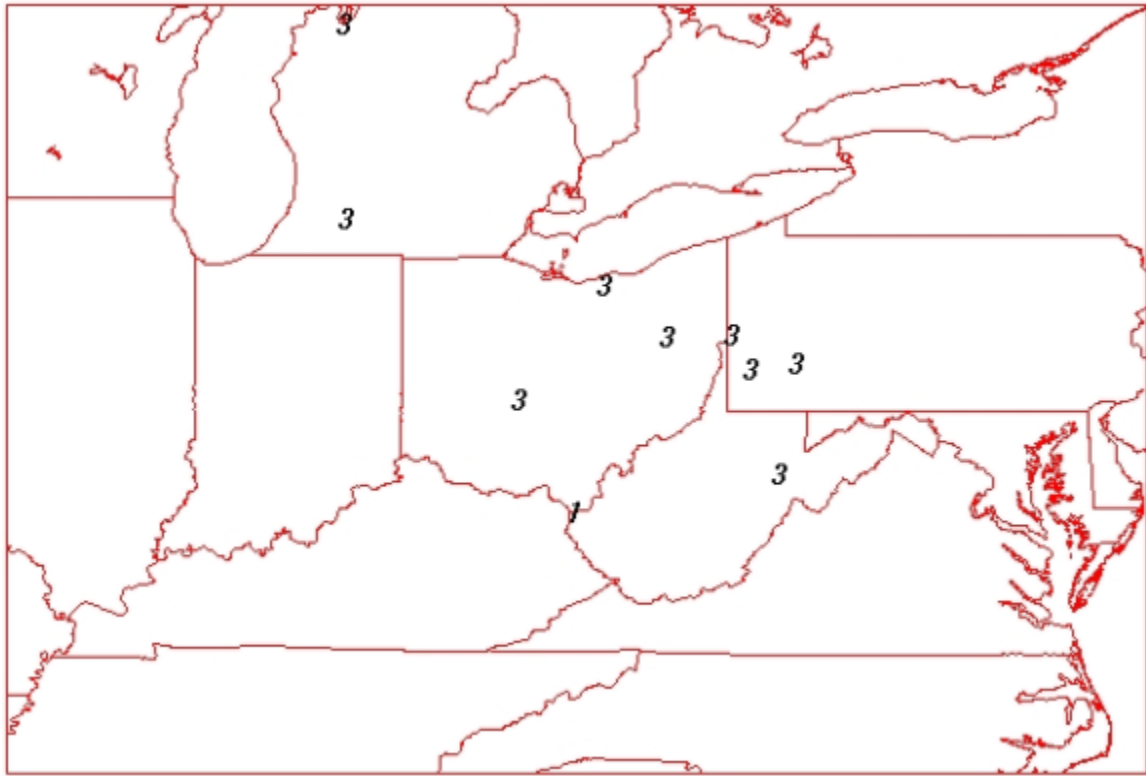


Fig. 2. Icing intensity PIREPS between 16 and 22 UTC on Feb. 13, 2003. '3' indicates light icing.

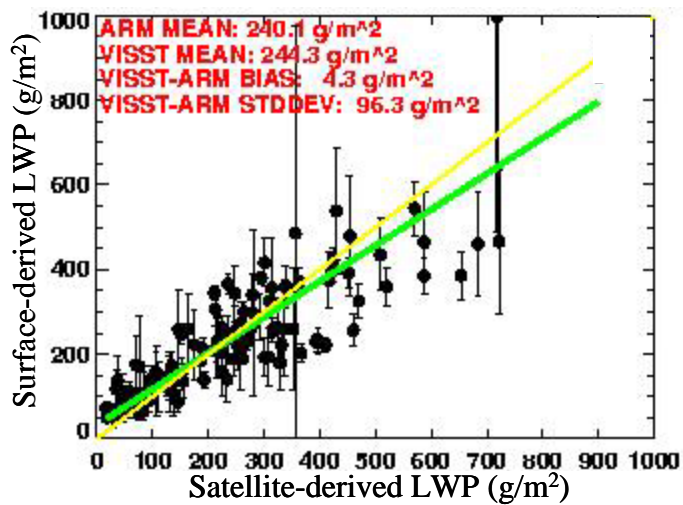


Fig. 3. Comparison of satellite derived liquid water path (LWP) with surface-based microwave radiometer over Oklahoma in March 2000. 55% of points represent clouds composed of SLW.

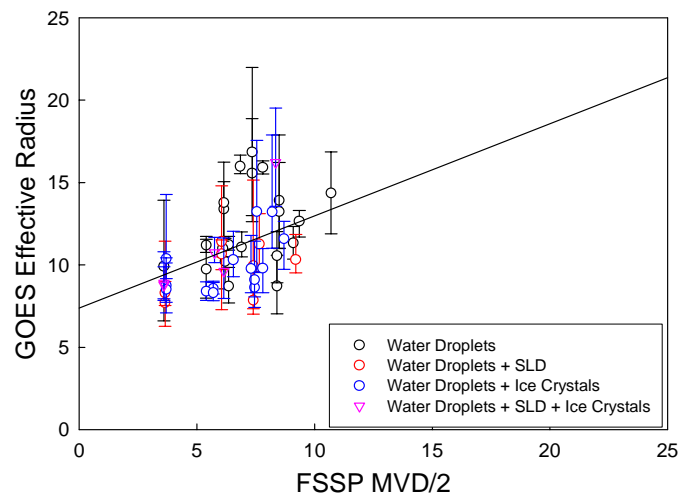


Fig. 4. Comparison of satellite derived effective radius with mean-volume radius derived from FSSP probe data obtained in SLW cloud top penetrations from the NASA Glenn Twin Otter in winter 1997/1998.

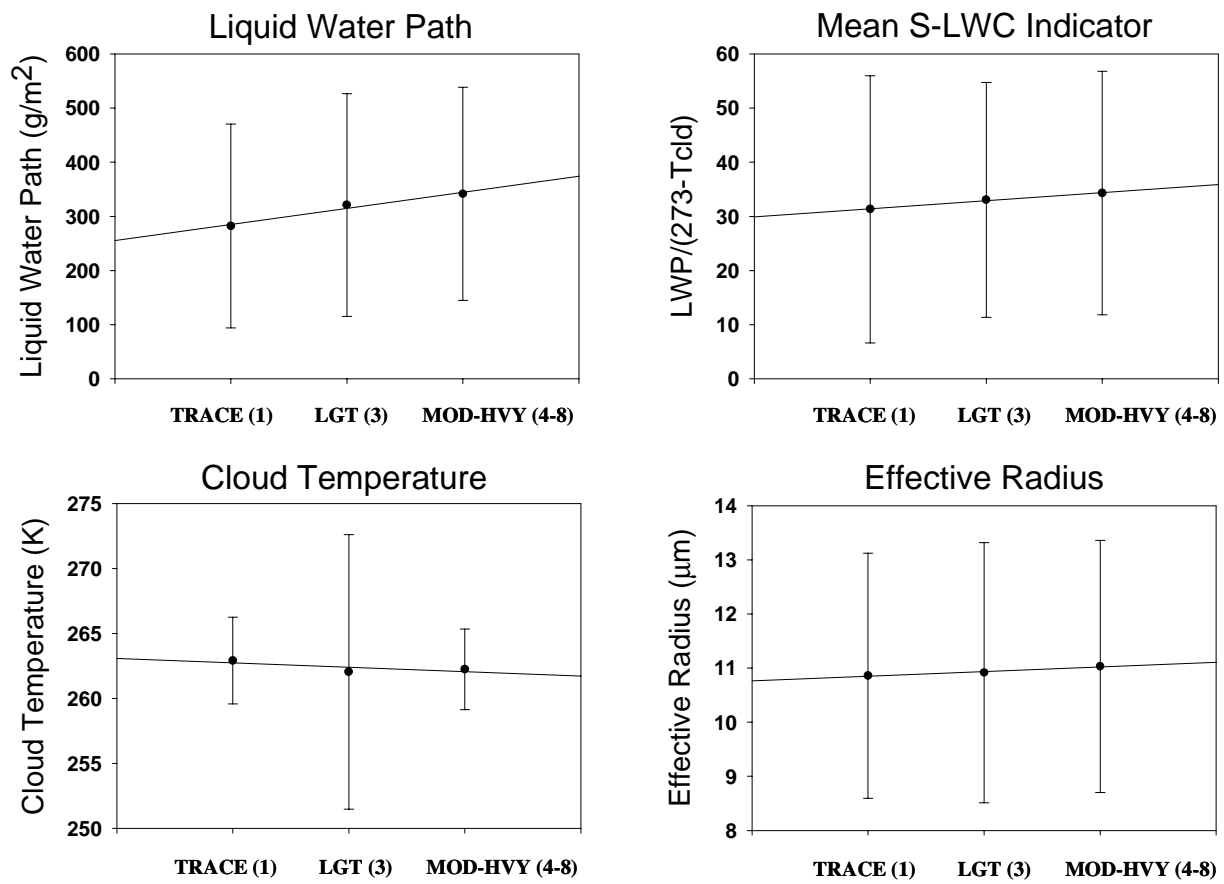


Fig. 5. Correlation between satellite-derived cloud parameters and icing severity reports from PIREPS.